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Road-rail intermodal freight transport as a strategy for climate change mitigation

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ABSTRACT

When attempting to reduce atmospheric emissions, a strategy commonly suggested by experts is the replacement of road transport with rail transport. However, in many countries and for many companies worldwide a complete transition to rail transport of freight is not feasible due to either a lack of available railway infrastructure or high investment costs. With that in mind, this paper aims to assess the potential of road-rail intermodal operations as a strategy to reduce atmospheric emissions, and thereby help mitigate climate change worldwide. This was achieved by quantifying and comparing emissions of CO_2, CO, CH_4, NO_x, hydrocarbons and particulate matter in a case-study that considered road-only and intermodal road-rail routes from 17 production facilities to their nearest port, according to International Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC) policies, as well as Euro V and EPA (United State Environmental Protection Agency) emission standards. The results showed that an intermodal road-rail operations would reduce emissions by up to 77.4%, be up to 43.48% more fuel-efficient and up to 80% cheaper than operating solely with road transport, posing as a viable strategy to enable more companies and countries to mitigate climate change.

1. Introduction

Through time, studies focused on industrial productivity and resource efficiency rose in the list of priorities of businesses and industries alike, leaving studies on supply chain management or environmental management aside. However, as intersections among these fields became more common, it also became clear that their interactions could no longer be ignored (Bontekoning et al., 2004; Zachariadis, 2005). Thus, a substantial growth in quantity and quality of multidisciplinary studies encompassing both supply chain management and environmental management has been perceived, especially in the last 10 years, mostly due to an increased awareness about the effects of atmospheric emissions on climate change (Stelling, 2014).

As the differences in efficiency and emissions between transport methods became more empirical, objective and precise, experts began to point out the importance that climate change mitigation policies target supply chain management as well, analyzing it

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separately and even setting specific emission limits and standards (Santos et al., 2010; Liao et al., 2009). Even though the international community and businesses have gradually accepted these new parameters and have started acting on them, results have not being achieved as fast as necessary to effectively promote large-scale supply chain sustainability and address the worldwide undesired effects of atmospheric emissions (Stelling, 2014).

Mayer et al. (2012) analyzed emissions and policies that point to potential benefits from completely replacing road transport with alternatives based solely on railways. In studies published by Stelling (2014) and Liao et al. (2009), investments in (a) universalizing rail gauges, (b) expanding international rail networks, and (c) modernizing loading terminals were suggested as strategies to improve transport operations and reduce freight costs, while simultaneously addressing environmental concerns.

More studies began to suggest other changes in freight transport behavior, such as switching from airplanes to ships, ships to ducts, etc. (Meisel et al., 2013). As a consequence, intermodal operations and energy efficiency became the two most common conclusions and recommendations (Chapman, 2007; World Bank, 2012).

As intermodal operations are progressively studied and highlighted as a less emission intensive and more energy efficient alternatives, its advantages have become more evident (Lammgård, 2012). The choice to shift from a road-only to an intermodal road-rail operation benefits from trains' main attribute: significantly larger load capacity than trucks (Janic, 2007). Positive results have been achieved even when considering inherent operational hindrances such as transferring goods from one vehicle to another. However, most studies on this topic focus solely on CO_2 emissions (Woodburn, 2012).

To assess the emissions of intermodal road-rail operations as regulated by the International Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC), this paper quantifies CO_2 emissions as well as CO, CH_4, NO_x, hydrocarbons and particulate matter. Current global legislation and policies on atmospheric emissions and climate change mitigation are taken into consideration. Furthermore, in order to empirically substantiate the discussion, a case-study is presented to verify the potential of intermodal road-rail operations to reduce emissions from road-only transport. Through the results of this paper, the authors expect to further support decision-makers and policy-makers on the use of intermodal freight transport operations as a strategy for climate change mitigation when complete replacement of road for rail is not feasible.

1.1. Roads, rails and intermodal operations

In supply chain management, transport logistics is one of the key components to ascertain the availability of goods and raw materials (Crainic, 2003). Considering that throughout the last 30 years many business operations worldwide became more global, using a single transport modal became uncommon, due to long-hauling needs. To enable goods and materials to be transported by different types of vehicles, solutions such as containers were created, which enabled easier operational routines inside terminals. Nowadays, containers are the most commonly used mobile storage units, and enable all modals of transport to better handle any type of goods (Crainic and Kim, 2007).

When using more than one modal, transport operations can be classified as (a) multimodal, if different mobile storage units are used; (b) intermodal, when using a same mobile storage unit; (c) co-modal, when used cooperatively by more than one shipper, and (d) synchromodal, when the choice of modals is flexible according to operational circumstances (Crainic and Kim, 2007). The most common applications of these operations are intermodal links between roads and rails to supply sea ports, which grew significantly in importance due to continuous pressures from the environmental sector, bringing efficient and effective solutions to reduce costs and improve supply chain performance (Ghiani et al., 2013).

Trucks are the most popular vehicles in the transport sector due to their (a) reach, ability to deliver to most destinations; (b) flexibility, capacity to operate on virtually any country's roads; (c) speed, especially on short routes; (d) low costs, due to simplified maintenance and handling requirements; and (d) low investment requirements. However, there are inherent disadvantages of using road trucks for transport, such as: (a) susceptibility to traffic in urban environments; (b) accidents or breakdowns due to exposure to poor road pavement or unfavorable weather; (c) limited load capacity for business operations that require the displacement of great

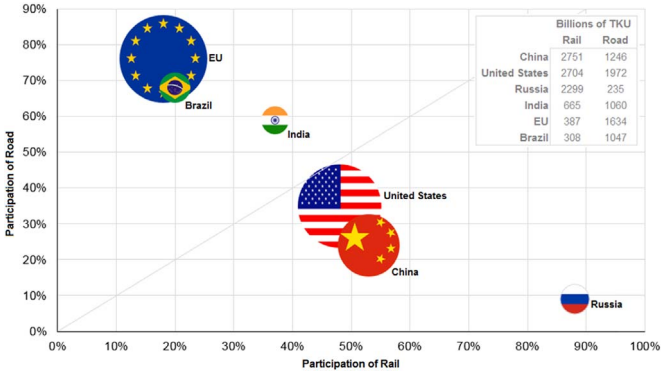

Fig. 1. Participation of roads and rails in freight transport in 2014 (size of the circle represents Gross Domestic Product - GPD). **Observation**: Unit of Tonne-Kilometer (TKU) is the result of multiplying total load carried (TLC) in tons by total distance covered (TDC) in kilometers).
Sources: ANTF (2015), Eurostat (2015), World Bank (2016) and European Parliament (2015).

quantities of materials over long distances; and (d) high emissions of gases associated with climate change due to fuel combustion (Guoquan et al., 2014; Reis et al., 2013).

Trains do not have the same reach nor are they as flexible as trucks, however, their characteristics favor the transport of great quantities of materials over long distances, and thereby avoid most problems related to weather and traffic (Guoquan et al., 2014; Reis et al., 2013). These advantages come at higher investment and maintenance costs, however, trains' reliability and significantly lower fuel consumption per transported ton have placed this modal among the favored alternatives to reduce atmospheric emissions derived from transport activities (Ghiani et al., 2013).

Fig. 1 shows different patterns in road and rail participation in freight transport within the three largest global economies and the three most representative emerging economies.

Fig. 1 shows that focusing on either roads or rails can serve a nation's transport needs; however, rail-oriented economies such as Russia, the United States and China transport greater amounts of goods and materials through their territories. Considering that worldwide, diesel is the most commonly used type of fuel for both road and rail freight transport operations (IEA, 2015; ERF, 2015), one could assume that Russia, China and the United States consume substantially more diesel than their equivalent GDP counterparts.

However, according to OPEC (2011), rail-oriented countries tend to consume less diesel in freight transport activities, a fact that reinforces the previously discussed advantage of trains for hauling large quantities of goods over long distances. Therefore, why are all countries not gradually migrating their modal distribution towards railways?

Worldwide, the construction of freight railways costs, on average, between US$ 900 thousand and US$ 3 million per kilometer, including earthwork, labor, materials, signaling and safety measures (Baumgartner, 2001; Von Brown, 2011). Roads, on the other hand, rarely exceed US$ 1 million per kilometer, and can be built up to 40% faster (Chong and Hopkins, 2016). Demand management and construction lead-time planning are also factors that often favor the choice of building roads instead of rails, as well as the acquisition of more trucks instead of wagons and locomotives (Lam and Gu, 2016).

Nevertheless, the benefits of railways remain appealing, especially regarding atmospheric emissions: in 2012, 23.1% of global CO_2 emissions were derived from transport, 3.6% of which were caused by the rail sector (IEA, 2015; ERF, 2015). Since 1975, freight activity overall increased by 78%, especially in the United States, China and Russia, however, the relative contribution of rails to total CO_2 emissions in worldwide freight transport was almost halved (− 42%) in the same period. In Europe, most of this reduction comes from replacing diesel locomotives with electric or hybrid diesel-electric locomotives, which now account for more than 72% of the fleet (IEA, 2015; ERF, 2015).

In order to enable companies and countries in which road transport is the main transport modal to improve their atmospheric emission performance without compromising large amounts of capital, or requiring, long periods of time to construct railways, using intermodal road-rail can be a short-term solution (Lam and Gu, 2016). Operationally, the easiest and most recommended way to transition from road to rail is to use existing trucks to supply the nearest existing railway that leads directly or indirectly to the desired destination, preferably without the need to use trucks again at the destination end of the long-haul rail (Lam and Gu, 2016).

Connection between trucks and trains is handled at a continental/inland terminal, often composed of at least: (1) road access with waiting area for the trucks; (2) a check-in point; (3) rail access; (4) a transshipment area – where cranes and other handling equipment operate over loading lanes to move containers from one vehicle to another –; and (5) a storage area. That said, three factors favor the road-rail intermodal in terms of infrastructure and costs: (a) cooperation between rail and road logistics operators has been streamlined throughout the years and can efficiently handle containers; (b) most existing rail terminals were already built with the required areas to support truck operations; and (c) many rail lines worldwide would benefit from having additional customers to improve the scale of their operations and reduce costs, further boosting their competitiveness (Lam and Gu, 2016).

When addressing atmospheric emissions, using road-rail intermodal operations induces companies and logistics operators to use trucks in the situation in which they are most fuel efficient – short distances –, while simultaneously making use of trains in their most desirable emission conditions: fully loaded over long distances. Furthermore, removing trucks from long distance routes favors traffic, and reduces chances of accidents and breakdowns caused by either human failure, maintenance issues or adverse weather (IEA, 2015; ERF, 2015).

1.2. Climate change mitigation strategies in the context of freight transport

In view of the advantages of road-rail intermodal operations as a possible short-term solution to reduce atmospheric emissions, it is important to understand which emission reduction strategies can benefit the most from this shift in transport modal.

During the sixteenth Conference of the Parties (COP), in 2009, the Copenhagen Accord came into force and its goal was that signatory countries adopt voluntary mitigation measures to prevent global mean temperatures from rising above 2 °C, widely agreed as the "tipping point" at which significant changes will occur in climatological processes throughout the planet, such as increased sea levels due to melting of glaciers and ice caps, which may cause huge economic and social losses (Lau et al., 2012).

Gases generated by vehicles powered by fossil fuels such as diesel have been responsible for significant amounts of atmospheric emissions in urban areas, contributing to global warming by enhancing the greenhouse effect (Cames and Helmers, 2013). Studies also show that individuals exposed to gases such as nitrogen oxides, carbon monoxides and particulate matter emitted by diesel engines have a higher risk of developing respiratory and cardiovascular problems (WHO, 2016).

Furthermore, due to the fact that black carbon represents the majority of diesel's particulate matter emissions, decreasing diesel consumption is especially desirable when no filters for particulate matter and fine dust are employed (Cames and Helmers, 2013). Black carbon is a strong atmospheric warming agent that is not regulated by the Kyoto protocol and, depending on the time horizon, the global warming potential (GWP) of black carbon can be up to 4470 times greater if compared to that of CO_2 (Jacobson, 2007).

However, since 2013, transport associations from Asia, Europe and Latin America have developed programs under the Global Green Freight Action Plan that attempt to promote the integration of black carbon into mitigation strategies (Cames and Helmers, 2013).

Although the atmosphere naturally contains gases such as nitrogen oxides (NO_x) and carbon dioxide (CO_2), anthropogenic emission levels currently compromise the effectiveness of natural processes of self-regulation and are threatening many ecosystems (Jaroszweski et al., 2010; Marsden and Rye, 2010). Consequently, many countries worldwide have implemented legislation that seeks to progressively improve engine efficiency and quality of fossil fuels in order to reduce the emission of carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC), particulate matter (PM), aldehydes, CO_2, methane (CH_4) and sulfur oxides (SO_X) (Eng-Larsson et al., 2012). Yet, legislation alone has not been enough: rethinking when and how each type of vehicle is used represents what specialists and researchers configure as the largest contributions to emission reductions (Janic, 2007; Chunark et al., 2015).

During the 2014 UN Climate Summit, public and private sector representatives articulated strategies for future freight and passenger transport that would avoid worldwide mean temperatures from rising above 2 °C, as determined by the Copenhagen Accord (UN, 2014b). Brazil, for example, had pledged to reduce its estimated pollutant emissions (3236 $GtCO_2eq$) by between 36.1% and 38.9% (1,168$GtCO_2eq$ and 1,259$GtCO_2eq$) by 2020, considering the 2005 business-as-usual baseline (UNFCCC, 2011); during COP 2015, these figures were updated to 37% (1,197$GtCO_2eq$) by 2025 and 43% (1,391$GtCO_2eq$) by 2030, considering the same baseline (CarbonBrief, 2016).

The resulting strategies from these meetings rely mostly on incentives for technological improvements in energy generation and distribution, as well as more efficient supply chain operations. However, given expected growth in transport, it was also considered imperative that carbon intensive transport (e.g. road and air) seek alternatives in rail. As a consequence, the International Railway Association (UIC) was the first organization to set global targets for increasing the share of railways' participation in freight transport by attaining the same participation as that of road by 2030, and surpassing it by 50% by 2050 (UN, 2014a).

The European Commission and the IPCC also defined a gradual transition from roads to rails, especially in freight transport, as one of their goals for 2030 and 2050. The main argument for adoption of this strategy is based on the fact that most of the existing strategies (e.g. fuel taxes, fuel and engine emission standards, biofuel subsidies, transport planning and zoning, fuel labelling) are no longer considered sufficient to achieve the desired emission reduction targets. By using modal shift as a strategy, these international organizations expect to increase the speed by which urban air pollution, land-use competition, urban noise, health impacts, diesel dependency and road accidents are reduced throughout supply chains (UNEP, 2012; Den Boer et al., 2011).

Even though some of the aforementioned strategies for achieving emission targets are strongly criticized by some countries, greater commitment was perceived from large emerging economies such as India, China, Russia and Brazil, when compared to highly developed countries within the Kyoto Protocol (Lau et al., 2012).

Still, attempting to increase rail participation in supply chains worldwide, whether by completely replacing other modals or by including it in intermodal operations, is a task that cannot be undertaken indiscriminately; indeed, it is important to analyze emissions from rails in comparison to the modal they intend to replace. Measuring emissions according to internationally accepted standards not only enables objective and direct comparisons, but also decision-makers and policy-makers ability to verify how much this modal shift can actually contribute to climate change mitigation, if broadly employed as a tool (IEA, 2015; ERF, 2015).

Among the existing emissions standards, the Euro series, which came into force in 1990, can be highlighted as the most commonly used standard for road transport emissions worldwide and is currently in its sixth phase of implementation, known as Euro VI (CEC, 2007). Countries such as the United States, on the other hand, have their own regulatory agencies and standards, e.g. Environmental Protection Agency (EPA), for both road and rail vehicles, which are often complemented by state and municipal legislation. For rail vehicles, the most commonly employed emissions standards worldwide are those from the United States' EPA, which sets limits for CO, HC, NO_x and PM. The latest implementation phase is called Tier V and came into force in January 2015, setting standards for both newly manufactured and remanufactured train locomotives (EPA, 2012).

The aforementioned standards focus on diesel engines, however, the fuel itself can affect emissions just as much as the engine. Specifically, CO_2 and sulfur emissions can be reduced by the formulation and use of less polluting fuels, for example, different mixtures of diesel with B-100 biodiesel, all of which result in fuels with lower sulfur content (EIA, 2011). Furthermore, diesel's sulfur content is directly related to the amount of fine dust and particulate matter emitted when no filters are employed (Wall et al., 1987), this being an additional reason why legislation worldwide is reducing sulfur concentrations in diesel fuel.

2. Methods

In order to reinforce the road-rail intermodal as an alternative to road only transport operations worldwide and propose it as a climate change mitigation strategy for countries and companies with fewer resources to achieve their emission reduction goals, this paper compares the emissions of CO, HC, NO_x, CO_2, CH_4 and PM generated by road-only and road-rail intermodal transport, in a case-study that consists of displacing the Brazilian paper and cellulose pulp sector's average monthly export of 3200 t, from production facilities to its nearest port (BRACELPA, 2013). This case-study was chosen based on four criteria:

(a) **Intensive use of road transport:** Brazilian road transport is responsible for 68% of the country's total displacement of goods, affecting 73% of its GDP (Hijjar and Lobo, 2011);
(b) **Products which amount to significant transport needs:** Brazil is one of the three largest producers and exporters of paper and cellulose pulp worldwide, representing 7.6% of global production (BRACELPA, 2013; Farinaci et al., 2013);
(c) **Products with significant road-related transport emissions:** The World Bank Report on Inclusive Green Growth states that emissions from transport of paper and cellulose pulp products represent over 30% of total pollutant emissions generated

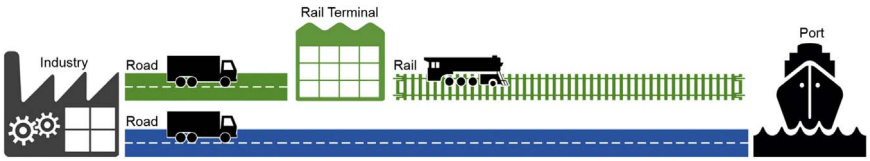

Fig. 2. Graphical representation of the analysis. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

throughout their supply chains – 90% of which come from trucks (World Bank, 2012); and

(d) **Railway infrastructure that inhibits a complete shift from roads:** Available data (Barros and Lobo, 2009; Fleury, 2012) as well as two surveys, one of which was conducted by a private supply chain management consulting company (OECD, 2015) and the other was conducted by the Institute of Logistics from the Federal University of Rio de Janeiro with 370 supply chain management professionals (ILOS, 2009), pointed out that unavailability of routes, total costs, lack of carts/wagons, low speeds, lack of terminals and infrastructure and low reliability are the main barriers preventing full transitions from road to rail.

When compared to countries with similar GDP (e.g. Russia and India) or similar geographic proportions (e.g. United States and China), Brazil's heavy reliance on road transport (as seen in Fig. 1) presents great potential for deployment of intermodal operations as an alternative to mitigate climate change. Considering the increased engagement of emerging economies in comparison with other countries towards achieving global environmental targets, as well as the economic and operational difficulties stated by Brazilian supply chain management professionals in promoting improvement and expansion of railway infrastructure, the authors believe that a Brazilian case-study is capable of setting a valid example for atmospheric emission reduction in worldwide transport operations. Fig. 2 shows the approach adopted for the case-study's comparison between road-rail intermodal (green) and road-only operation (blue).

Together, the 17 companies considered in the case-study represent more than 75% of the total paper and cellulose pulp production in Brazil (BRACELPA, 2013). The case-study comprises the distances between each of their 17 production facilities to their closest port (Fleury, 2012), as shown in Table 1. Road distances were chosen considering two criteria: (1) pavement compatible with operation of heavy-duty trucks (CNT, 2015), and (2) shortest possible distance between each production facility and its destination (port or railway loading terminal, when applicable). Rail distances of the proposed intermodal operation were chosen based on two criteria: (1) closest loading terminal available to the production facility, and (2) shortest single-trip rail route to the port of destination. Whenever possible, the distances were acquired directly from the industries involved. When such data was unavailable, distances were defined by approximation using online satellite imaging services.

Table 2 shows the equations and variables used to develop this paper. Both equations used for calculating emissions were created based on the equations provided by EPA (2012), UNFCCC (2012) and GHG Protocol (2013).

For purposes of calculating emissions in road transport, Euro V limits were applied to the average characteristics of the bestselling trucks in Brazil, operating at an average speed of 65 km/h (Barbosa, 2012). Vehicle selection criteria were: a) total gross weight (TGW) of 23,000 kgf - 16 t load capacity; b) engine power between 290 and 310 hp (213 and 228 kW) and; c) 6 × 4 chassis structure. The selected models were equivalent to each other, having the configuration most commonly used in the transport of paper and cellulose pulp in Brazil (Fleury, 2012).

Table 1
Distances considered for the case-study.

Production facility	Road only	Road-rail Intermodal	
	Distance (km)	Rail fraction (km)	Road fraction (km)
Suzano	93.0	95.0	7.0
Embú das Artes	105.0	106.0	5.0
Caieiras	123.5	125.0	5.0
Jacareí	151.0	158.0	22.0
Jundiaí	149.0	155.0	19.0
Valinhos	190.0	192.0	8.0
Indaiatuba	184.0	199.0	8.0
Itapira	243.0	244.0	5.0
Piracicaba	251.5	253.0	6.0
Mogí-Guacú	265.0	268.0	11.0
Limeira	257.5	260.0	9.0
Angatuba	311.0	323.0	46.0
Luis Antônio	381.0	391.0	33.0
Curitiba	439.5	451.0	8.0
Arapoti	519.0	522.0	5.0
Belo Horizonte	667.0	659.0	9.0
Santa Luzia	682.0	701.0	18.0

Observation: Due to privacy and data disclosure agreements, production facilities were represented by the name of the cities in which they are located.

Table 2
Summary of equations, variables and units.
Sources: Hays (1990), EPA (1991), Runge (1998), Filas (2002), Kecojevic and Komljenovic (2010) and Bassi (2012).

Equations	Variables		Units
$TE_{CO2} = \frac{EF \times P \times X \times L \times LF \times E}{D \times V \times C}$	TE	Total emissions	G
	EF	Engine specific fuel efficiency	kg/kWh
	P	Power	kW
	X	Distance	Km
	L	Load	Tons
$TE_{other} \frac{P \times X \times L \times E}{V \times C}$	LF	Load factor, from 0.18 (no load) to 0.50 (full load)	(non-unitary)
	E	Emission limits	g/L (CO_2) g/kWh (other gases)
	D	Fuel density	kg/L
	V	Average speed	km/h
	C	Vehicle load capacity	Tons

The rail fraction of the intermodal operation had its calculations consider EPA Line-Haul Tier III emission limits for a line-haul train with diesel-electric locomotive engines between 2900 and 3800 hp (2132 and 2794 kW), operating at an average speed of 25 km/h to haul 120 80-ton carts/wagons at full capacity (Fleury, 2012). These characteristics represent over 75% of the vehicles operating on Brazilian railways (Fleury, 2014).

All vehicles were considered to be operating with diesel B-S10 (best variation of ultra-low-sulfur diesel available in Brazil), which has 5% biodiesel in its composition and proven ability to reduce emissions of CO_2 and SO_2, while stimulating improvements in diesel engine technologies, and fostering production of cleaner fuel (DieselNet, 2000; Gilpin et al., 2014;).

Engine operation patterns were set to the European Transient Cycle (ETC), which is best suited for normal business conditions in comparison to the European Load Response Cycle (ELR) and the European Stationary Cycle (ESC) (Johnson et al., 2013; Payri et al., 2009). Table 3 summarizes the data considered for the calculations.

3. Results and discussions

Fig. 3 presents the main results obtained by applying the methodology to calculate the emissions generated by cargo displacement within the parameters of the case-study. The results clearly demonstrate that road-only transport is much more polluting than road-rail intermodal transport.

The favorable results in Brazil suggest that road-rail intermodal operations as a climate change mitigation strategy could be applicable in other countries. When kept in mind that the 17 companies considered in the case-study represent over 75% of total Brazilian production of paper and cellulose pulp products, and that 90% of the transport emissions from this industry are from road only transport, the results presented in Fig. 3 become even more relevant. Considering that many companies and countries worldwide have similar or even worse conditions than those identified in this case-study, the global potential for emission reduction becomes more evident, especially when availability of investments into new railway infrastructure or full rail operations are a hindrance.

If replicated not only in other nations' paper and cellulose pulp industries but in industries from other sectors as well, road-rail intermodal operations as a strategy for climate change mitigation would expand its reach and potential benefits. Commodities' production activities such as mining, metallurgy and agriculture – which commonly rely on long-distance transportation of large quantities of raw materials and intermediary goods – would pose as promising candidates to further contribute to emission reductions worldwide by shifting from road-only to road-rail intermodal operations.

Substantial reductions were seen especially for PM, CO_2 and CO emissions, all gases which are directly addressed by international initiatives concerned with human health, the greenhouse effect and global warming. These results seen in Fig. 3 were then confirmed

Table 3
Emission limits and data considered for the calculations.

Standard	Scenario	Emission limits (E)[e,f]					Data considered for the calculations[g]						
		CO_2[a]	CO	PM	NO_x	THC[b]	C	V	P[c]	EF[c]	L	LF[d]	D
EPA Line-Haul Tier III	**Road-rail intermodal**	2.547	2.010	0.134	7.370	0.402	3200	25	2500	28.000%	3200	0.50	0.85
Euro V	**Road only**	2.547	4.000	0.030	2.000	1.650	16	65	220	36.325%	3200	0.50	0.85

[a] Within the chosen standards, CO_2 emissions are not bound to limits because they vary according to fuel type and consumption (ISO, 2006). CO_2 emission limits can be found in EU Regulation No. 443/2009, however they are not applicable to the vehicles under study, nor to the chosen fuel.
[b] Emission limit for total hydrocarbons (THC): HC + CH_4.
[c] Considered as delivered at the crankshaft (theoretical). Manufacturers chose not to provide power and efficiency data as delivered to the wheels.
[d] As seen in Table 2, load factor (LF) is a non-unitary factor that varies from 0.18 (no load) to 0.50 (full load).
[e] EPA Line-Haul Tier III emission limits were converted from horsepower-hour (hp.h) to kilowatt-hour (kWh).
[f] CO_2 measured in g/L; other gases measured in g/kWh.
[g] The acronyms correspond to the variables in Table 2.

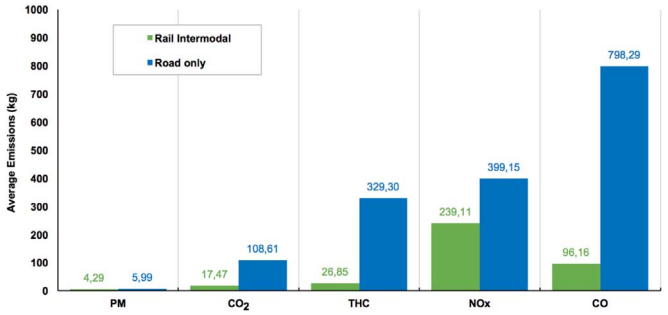

Fig. 3. Average emissions of the 17 routes in the case-study, for all pollutants.

when each pollutant was also analyzed based on total emissions as a function of either distance (g/km) and load displacement (g/TKU), according to the parameters of the case-study, as seen in Fig. 4. Once again, the road-rail intermodal was significantly less polluting than a road-only operation, showing that using this modal shift as a climate change mitigation strategy can have its results perceived from multiple angles.

Most of this difference arose from the fact pointed out above that trains are better suited to transport large loads than trucks, requiring fewer trips and therefore making road-only transport less fuel-efficient. The results show that the road-rail intermodal operation would consume a mean of 2.14 L/t (7.16 L/10^3TKU) to transport the same load as the road-only operation, which consumed 13.33 L/t (44.50 L/10^3TKU).

Furthermore, by jointly analyzing the results shown in Figs. 3 and 4, the authors noticed different emission patterns between road-only and road-rail intermodal operations. This occurs due to the differences in engine operation at load and fuel combustion efficiency, as described in Section 2. In Fig. 4, the polygon that represents road-only emissions is significantly larger in every direction, particularly on the vertex that represents CO emissions – a gas directly linked to the greenhouse effect –, as a consequence of partial combustion in less efficient engines. To further analyze specific differences in emission patterns between road-only and road-rail intermodal operations, Fig. 5 presents the composition of each transport method's emissions.

Upon further analysis of the results depicted in Figs. 4 and 5, the road-rail intermodal showed a higher tendency to generate NO_x emissions, a group of gases associated with the formation of smog and acid rain, which occurs due to the early combustion oxidation of nitrogen in the reduced atmosphere that exists inside larger engines (Cames and Helmers, 2013). Even though the road-rail intermodal tends to emit proportionally more NO_x during its operation (61.69%, Fig. 5), the results of this case-study showed that road-only transport emitted almost 70% more of it in total (399.15 kg, Fig. 3).

Additionally, despite the high CO composition of road-only emissions, the worst emissions in total were those of total hydrocarbons (THC), a group of gases also associated to the greenhouse effect: road-only transportation of goods generated 329.30 kg of this pollutant, while the proposed road-rail intermodal would generate 26.85 kg (Fig. 3).

At this point in the development of this paper, it was also possible to estimate the potential emission reductions that could take place if all of the 1047 billion TKU displaced in Brazil during 2014 had been transported by road-rail intermodal operations as exemplified in this paper's case-study (Fig. 6). Furthermore, diesel consumption in freight transport would decrease up to 43.48% when compared to 2013 (from 39.93 to 22.57 million tons). However unlikely it would be unlikely for a country to enforce a modal shift of such magnitude, these numbers serve the purpose of reinforcing the potential that road-rail intermodal operations have as a strategy to positively affect atmospheric emissions directly related to diesel combustion.

Once again it is important to note that a modal shift of this magnitude would be unlikely, however, emission reductions that range

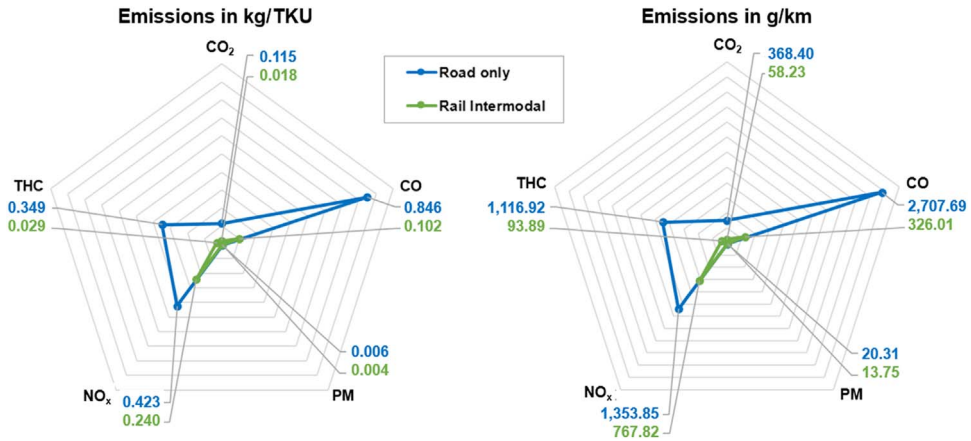

Fig. 4. Average emissions as a function of ton-kilometer and distance.

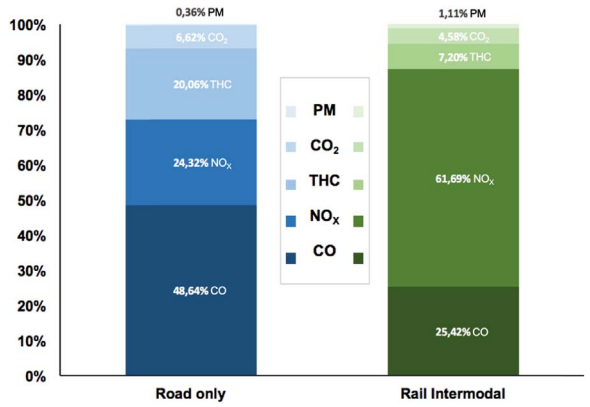

Fig. 5. Relative comparison between the composition of emissions of each modal.

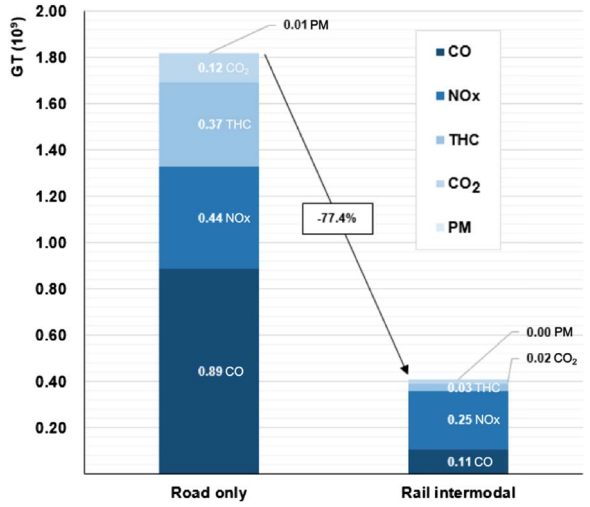

Fig. 6. Potential emission reductions from shifting from road-only to an intermodal operation.

up to 77.4% would be beneficial to countries and companies worldwide regardless of scale, especially when associated with consumption of up to 43.48% less diesel. Naturally, these results would vary in accordance to the productive and logistic characteristics of each company and would require case by case assessments *in loco*, nevertheless, insofar they do favor the adoption of road-rail intermodal as a climate change mitigation strategy.

Due to the lack of detailed data for Brazilian conditions, this paper did not consider pavement quality and micro-weather effects as variables, although it is known that these would increase emissions by reducing speeds and adding friction/abrasion to the operation. When experimenting with data from North American and European equivalents of these variables, road emissions

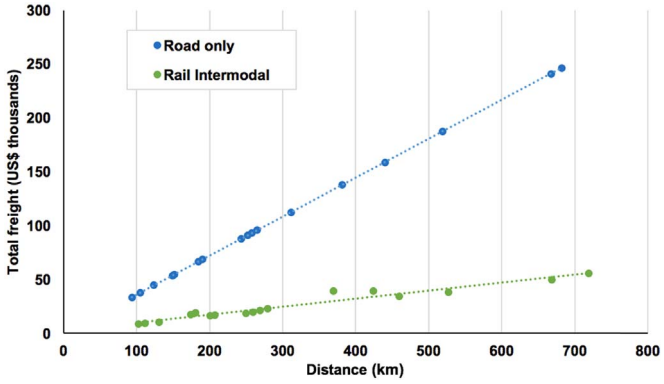

Fig. 7. Freight cost tendency as a function of increasing distances.

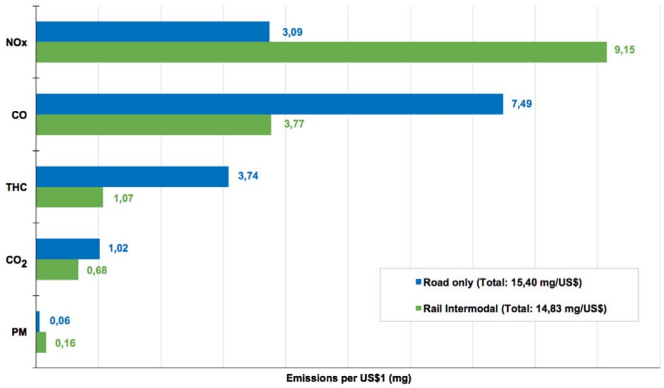

Fig. 8. Average milligrams of emissions per dollar spent on freight.

increased proportionally by at least 10% (up to 150% under extreme conditions), numbers which would be even higher if the worse conditions of Brazilians roads were to be considered (CNT, 2015; Bartholomeu and Caixeta Filho, 2009).

After analyzing the results up to this point, an additional discussion emerged among the authors: given the knowledge that transporting goods using a road-rail intermodal operation instead of road-only is substantially better in terms of emission reductions, would the difference in costs further justify this modal shift as a potential strategy for climate change mitigation?

In order to answer that, the authors made a primary assessment of how much it would cost for a company interested in contributing to climate change mitigation to hire logistics operators for either road-only or road-rail intermodal transport. To enable comparisons, calculations were made using average third-party freight prices in the industries where the case-study took place, this being the most important decision-making criteria when hiring transport services from a third-party company (Evangelista, 2014).

Fig. 7 shows the result of the aforementioned primary economic comparison between hiring transport services for either road only or road-rail intermodal operation. Results considered US$ 113/10^3 TKU for road-only transport on trucks with total gross weight (TGW) equal to 23,000 kgf and US$ 22/10^3 TKU for the rail fraction of the road-rail intermodal transport (Fleury, 2014; SEFAZ, 2013).

When compared to road-only transport, the freight costs of the road-rail intermodal alternative were substantially cheaper, varying between − 64% and − 80% when compared to road-only. Associating these results with those seen in Figs. 3–5, the authors confirmed the inverse proportionality that exists between freight prices and fuel consumption: the less fuel-efficient, the more expensive the freight – a known issue and common pricing practice among logistics operators (Evangelista, 2014).

This relation between fuel consumption and freight price was also analyzed alongside the emission results seen above. Fig. 8 shows how much emissions were caused by each freight dollar spent on each transport method.

Each dollar spent on transporting goods using road-only generated 15.40 mg of emissions, while the same one dollar spent on road-rail intermodal would generate 14.83 mg of emissions. The significance in this difference becomes even more substantial when Figs. 7 and 8 are analyzed together: on average, US$ 4.04 was spent on road-only transport for each US$ 1 spent on the road-rail intermodal operation, virtually making road-only transport 2.3 mg more polluting per dollar.

It is important to remind the reader that this primary economic comparison regards freights as charged from a third-party logistics operator, and not the costs and investments necessary to completely shift from one transport modal to another, nor the costs for a company to operate these transport modals by itself. However, knowing how substantial the emissions reduction argument is, it is an indicator that in-depth studies are necessary to calculate the full economic potential of changing from road-only to road-rail intermodal operations, be it in constructing new rail routes or in stimulating companies to change their third-party freight hiring behavior accordingly, based on the reality of their supply chains.

Knowing how much emissions each dollar spent on a given transport modal can generate is information that gives logistics professionals a new decision-making parameter towards potential climate change mitigation capability of the transport operations of their supply chains. Instead of compromising large amounts of capital to expand railway networks, countries and companies can seek road-rail intermodal operations as an alternative strategy to contribute to climate change mitigation targets.

4. Conclusions

The results showed that road-rail intermodal operations can be up to 77.4% less polluting than operating solely with road transport, in what regards to CO_2, CO, NO_x, CH_4, hydrocarbons and particulate matter. Additionally, results pointed to the road-rail intermodal operations as being up to 43.48% less diesel intensive (2.14 L/t, 7.16 L/10^3TKU) than road-only operations (13.33 L/t, 44.50 L/10^3TKU) when compared to current consumption levels. Thus, road-rail intermodal operations can be a viable strategy to help more countries and companies worldwide contribute to climate change mitigation.

Furthermore, a primary cost analysis showed that hiring a third-party logistics operator for road-rail intermodal transport services would be up to 80% cheaper than hiring a road-only solution. It was also estimated that each dollar spent on road-rail intermodal operations would generate up to 2.3 fewer milligrams of total emissions than that same dollar would if spent on road-only third-party

freight transport services.

Many countries that heavily rely on road transport have unfavorable railway infrastructure to enable full transitions to rail transport, making road-rail intermodal operations a transitional alternative that could help them achieve their emission reduction targets using their current infrastructure without unnecessarily compromising substantial long-term investments that could economically hinder their development in other segments.

Finally, the authors would like to make three recommendations for future studies or policies:

1. Creation of an international database that encompasses road pavement friction and abrasion indices, as well as road microweather conditions monitoring. This would enable engines and parts manufacturers and academics to improve the precision of their analyses and subsequent decision-making.
2. Development of studies associating the potential investment and technology transfer benefits of other existing climate change mitigation mechanisms and policies with the environmental benefits of road-rail intermodal operations. This would possibly enable identification of more strategies to better encompass different stakeholders from the supply chain management sector regarding global climate change mitigation targets set for specific regions or economic sectors.
3. Separation of industrial logistics, service sector logistics and public logistics within IPCC, UNFCC and COP emission targets, mechanisms and policies. This would enable logistics professionals to create business processes and structure operations that are more objective and precise in measuring and reducing their companies' specific emissions, as well as to better verify their contribution to national and global efforts.

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